NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3355

PRELIMINARY INVESTIGATION OF A STICK SHAKER AS A LIFT-MARGIN INDICATOR

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SUMMARY

An exploratory study was made to determine whether a pilot could use vibration of the control stick, in which either the amplitude or the frequency, or both, varied with lift or angle of attack, as a means of maintaining a desired lift margin below the stall. The study was made in the laboratory with several subjects, both pilots and nonpilots, by using an apparatus consisting of a control stick, a shaker, and shaker control equipment which provided varying amplitude and frequency with stick displacement. The tests consisted of having a subject attempt to maintain a given frequency and amplitude of vibration by moving the stick to compensate for an arbitrary change in frequency and amplitude imposed on the system by an operator independently of the stick motion. A brief study was also made to determine the minimum change in frequency or amplitude a subject could detect.

The results of these tests indicated that, once established, a given flight condition could probably be maintained by sensing variations in stick vibrations at least over the period of time covered by the tests (35 seconds), provided that the allowable variations from the desired flight conditions produced changes in amplitude of vibration of about 100 percent or changes in frequency of about 40 percent, or both. In the ranges of amplitude and frequency covered in the tests, sensitivity to amplitude changes increased with increase in amplitude and frequency; sensitivity to frequency changes did not appear to be materially affected by amplitude.

INTRODUCTION

Artificial stall-warning devices in the form of stick shakers have generally been most acceptable to pilots because the warning is transmitted to the pilot as a vibration which does not interfere with the receipt of other information by the various senses. For similar reasons stick vibration appears convenient as an indicator for holding a desired margin of angle of attack or lift coefficient below the stall in the landing approach. In order to shorten the landing runs or, for the case of carrier landings, to lower the arresting-gear loads, it is desirable to approach at as high an angle of attack as possible consistent with the following requirements: satisfactory stability and control characteristics, sufficient speed for satisfactory engine acceleration and waveoff, and an adequate margin below the stall to allow for air turbulence and to provide for a flight-path adjustment and flaring. Some work has been done toward using the stick shaker as a landing-approach-condition indicator as well as a stall-warning indicator by providing two stages of stick vibration of different frequency and amplitude, one actuated at the angle of attack desired for the landing approach and the other actuated at the prescribed stall-warning margin. This arrangement does not, however, appear to be entirely satisfactory because it would supply no indication of the magnitude of variations from the desired flight condition, which would therefore be difficult to maintain. The question has arisen as to whether a desired lift coefficient or angle of attack could be maintained by the pilot with sufficient accuracy if he were provided with a continuous angle-of-attack or lift-coefficient detector which would supply a continuous variation of either stick-shaker frequency or amplitude, or both, over the desired range of lift coefficient.

Exploratory tests were therefore made in the laboratory with simulator equipment to determine how well a subject could maintain a given stick-shaker frequency and amplitude by movement of the stick in an effort to compensate for an imposed arbitrary change in frequency and amplitude, simulating, for example, a change such as might be associated with a change in angle of attack in flight. For these preliminary tests a large number of discrete changes in either frequency or amplitude, or both, with change in stick position were used instead of a continuous variation which could not be obtained with the available equipment. Some tests were also made to determine the average minimum change in stick-shaker frequency and amplitude that a subject could detect. The tests covered an amplitude range from about 0.006 to 0.3 inch (measured near top of stick) and a frequency range from about 4 to 26 cycles per second.

APPARATUS

For the simulator tests a shaker was desired in which the frequency and amplitude could be varied independently. The available shaker that most nearly fitted these requirements was a pneumatic device used for tamping sand in foundry work. The shaker consisted of a double-acting piston-cylinder combination equipped with a slide valve. The travel of the cylinder was cushioned at each end by means of springs or rubber buffers between the ends of the cylinder and the ends of the piston rod which extended through the ends of the cylinder. The shaker was attached to the control stick by one end of the piston rod (fig. 1).

The frequency of the shaker was varied by means of a relay arranged to oscillate the slide valve. The relay operated on intermittent current supplied through a rotary switch turned by an electric motor. The speed of the motor, and hence the frequency of the shaker, was varied by varying the voltage to the motor.

The amplitude of vibration of the stick was varied at a given frequency by varying the pressure of the air supplied to the shaker.

The amplitude and frequency-response characteristics of the stick and shaker combination are shown in figure 2 for the shaker with rubber buffers between the ends of the cylinder and ends of the piston rod. Sample wave forms are also shown in figure 2. The double amplitude of vibration was measured on the stick just above the shaker. The response characteristics are very similar with springs in place of the rubber buffers, except that the maximum amplitudes attained were somewhat smaller.

For the first phase of the simulator tests, a continuous variation of frequency and amplitude with variation in stick position was desired. However, because of mechanical complexities, a design permitting such a variation could not easily be obtained. A less complex mechanical and electrical arrangement permitted changes in stick position to produce discrete changes in motor voltage and air pressure and hence discrete changes in frequency and amplitude. This system was therefore adopted. The apparatus was constructed to allow disturbances simulating, for example, an angle-of-attack change in flight to be imposed on the system by making available to the operator of the equipment a disturbance-input control by which the frequency and amplitude of stick vibration could be changed from a given or reference frequency and amplitude independently of stick position.

A schematic diagram of the arrangement is shown in figure 3. Four disturbance rates as determined by cam speed and cam shape were available to the operator. The range of the difference between stick displacement and disturbance-input-cam displacement, over which shaker operation was desired, was divided into 11 parts (steps), each of which closed a switch through a switching cam. Each switch was arranged to actuate some preset frequency and amplitude of the shaker through relays, resistances, and air-pressure valves (fig. 4). The displacement of the disturbance-input cam and the difference in displacements of the stick and the disturbance-input cam were measured in the tests by using NACA slide-wire control position transmitters.

The ideal functional characteristics of the apparatus for the first phase of the tests are illustrated by the block diagram in figure 5. In addition to the vibrational frequency and amplitude signals from the shaker, the subject may have also gained clues from the noise of the stick shaker and the air valves, a light spring-force feedback to the stick, and the inertia of the cams. An attempt was made to take out the spring-force feedback by an additional mechanical linkage and to mask the noise by playing back shaker noise previously recorded on tape.

For the second phase of the tests, it was desired to determine the minimum change in frequency or amplitude that a subject could detect. For this purpose, the frequency and amplitude step-control equipment of figures 3, 4, and 5 was disconnected. The amplitude was varied by manual operation of an air-pressure valve and the frequency was varied by manual operation of rheostats controlling the voltage to the frequency-control motor.

No provision was made for determining the effect of various steady stick forces on the ability of the subjects to sense changes in vibration. When the stick position was near neutral, it could be balanced against the light spring of the control position transmitter which measured the subject's output; otherwise it was overbalanced.

PROCEDURE AND RESULTS

Ability of Subject To Maintain a Selected Stick-Shaker Frequency and Amplitude

Description of tests.- Tests were made to determine how well a subject could maintain a selected stick-shaker frequency and amplitude when arbitrary disturbances in the form of amplitude and frequency changes were imposed on the system. Two of the representative variations of frequency and amplitude with stick displacement that were tried are shown in figure 6. The variations of stick vibration tried were based on the premise that, in an actual application, the intensity of the vibration should start at zero at some angle of attack well below the stall and increase to an uncomfortable level just before the stall to provide a warning. Variation in amplitude of vibration was therefore required, but it was believed that variation in frequency might be more accurately sensed in attempting to hold a given angle of attack. The arrangements tested, therefore, involved simultaneous variations of amplitude and frequency. Variation A, shown in figure 6(a), consisted of increasing the amplitude and frequency in 11 steps with rearward stick displacement. The maximum amplitude that could be attained with variation A was nominally 0.05 inch due to limitations of the equipment as evidenced in the frequency-response calibration (fig. 2). For variation B (fig. 6(b)) the amplitude increased while the frequency decreased in the 11 steps with rearward stick displacement. In variation B the ratio of the change in frequency from one step to the next to the frequency of the step was constant and the ratio of change in amplitude from one step to the next to the amplitude of the step was nearly constant. These constant amplitude and frequency ratios were made as large as possible for the ranges of amplitude and frequency obtainable with the equipment on the assumption that they would represent the maximum available equal stimuli between steps. (This equal-stimuli concept was based on Weber's law in psychology which states that the ratio of the change in stimulus to the total magnitude of the stimulus is a constant for the subject to just notice the change; see, for example, refs. 1 and 2.)

The rate of imposing the disturbances ranged, for frequency, between 0.08 and 8 cycles per second per second and, for amplitude, between 0 and 1.3 inches per second.

With variation A (fig. 6(a)) the subjects were instructed to select a step with a frequency and amplitude they thought they could most easily sense and then attempt to maintain, or null on, that step. For this type of variation, the subjects were also given a training period of about 10 to 15 minutes per day for about 10 days prior to the day of the tests. For variation B (fig. 6(b)), the subjects were asked to try to null on step 4. However, there were no training periods preceding the day of the tests using variation B since the training periods used with variation A appeared to have little effect on the subject's performance, although this was not conclusively determined. In each of the series of tests a standard type of disturbance (fig. 7) was introduced after the subject spent 10 to 15 minutes familiarizing himself with the variation of frequency and amplitude with stick displacement that was being used.

Results.- The results of the tests are shown in figure 7 for several subjects in the form of time histories of the difference in displacements of the stick and disturbance-input cam (labeled "subject output") and time histories of the disturbance input, both expressed in inches of equivalent stick displacement. The corresponding steps are indicated as the spaces between the horizontal lines which represent the switching points between steps. A perfect compensation would be indicated in the figure by a curve contained within one step. A fixed stick, or no compensation during a disturbance input, would be indicated by an output curve identical to the disturbance-input curve. Since perfect compensation could not be expected from a subject unless signals other than frequency and amplitude changes were being received, the best performance that could be obtained would be a one-step variation from the desired null.

Although more subjects (pilots and nonpilots) were tested with variation A than are indicated in figure 7(a), the results are shown principally for comparison with the results in figure 7(b) for the subjects who were available for both series of tests.

In figure 7(a), subjects 1 and 3 had little success in compensating for the disturbance, whereas subjects 2 and 4 had better performance. It is noteworthy that (see fig. 6(a)) the percentage changes in frequency and amplitude at the null points picked by subjects 2 and 4 were greater than for those picked by subjects 1 and 3. This would seem to indicate a correlation between performance and percentage change in stimuli as would be expected from Weber's law. The results in figure 7(b) (where all subjects nulled on step 4) indicate that, except where the most rapid changes occurred, the performance of all subjects was such that they permitted a change of only two steps from the null. The corresponding change in amplitude is about 120 percent and the change in frequency is about 40 percent (fig. 6(b)). It cannot be determined definitely whether the subjects were primarily sensing a change in amplitude or frequency or both (with variation B). For the conditions of variation A, however, the percentage amplitude variation was very much smaller than that for variation B; whereas the percentage frequency change was of similar magnitude. The subjects were therefore apparently using frequency as the primary reference with variation A and possibly also with variation B.

An important factor in the use of stick vibration as an indicator would be the ability to remember the feel of the vibration condition corresponding to a desired flight condition over a period of time sufficient to complete, for example, the final approach to landing, since no fixed reference is available as in a visual indicator. This factor was not investigated except to the extent of the time covered by the tests shown in figure 7(b), or about 35 seconds. Note that, in all cases in figure 7(b), at the end of the test the subjects had restored conditions to within one or two steps of the initial conditions or within 60 to 120 percent in amplitude and 20 to 40 percent in frequency.

From the foregoing results, stick vibration varying with angle of attack or lift coefficient appears to be usable as an indicator for maintaining a given flight condition, at least for a limited period of time, provided that the allowable variation from the desired flight condition, say 1° in angle of attack, produces either a change in amplitude of vibration of 60 to 120 percent or a variation in frequency of 20 to 40 percent, or both. It should be pointed out that sensing the feel of the stick vibration corresponding to a desired flight condition would probably require initially finding this flight condition by reference to some other indicator such as a visual dial indicator. Furthermore, vibrations transmitted to the stick from the airplane or the controls could have a detrimental effect on the ability of pilots to sense changes in vibrations from the stick shaker; however, this factor was not investigated.

Although a masking noise was used in the tests in an attempt to nullify any signal that a subject could be receiving from shaker and control-equipment noise, the effect of shaker and control noise and masking noise on the subject's performance was not conclusively determined. Some tests made with the masking noise turned off indicated no noticeable change in subject performance. A few tests were also made with the shaker and control equipment inoperative but with a slight force feedback due to the inertia of the switching cam and springs of the control-position transmitters present during the disturbance input. All subjects tested except one found sensing this force feedback as difficult as sensing vibrations, particularly in that no indication of the original null was available to the subject. One subject, however, was able to do better with inertia feedback than anyone was able to do with vibrations (results not shown). Nevertheless, the lack of a null indication over a long period of time was detrimental to his performance also.

Ability of Subject To Detect Changes in Frequency or Amplitude

Description of tests.- In the tests to determine the ability of a subject to detect changes in amplitude, the shaker was first set into operation at some predetermined frequency and amplitude and the air pressure was noted. After the subject held the stick for a few seconds or long enough to establish a feel of the level of vibration, the amplitude was increased or decreased more or less continuously at random rates by the operator through manual operation of the air-pressure valve. When the subject realized that the amplitude had changed, he signaled to the operator, who then discontinued the pressure change. The change in pressure from the original pressure was observed by the operator. Actually, the observed pressure change, and hence the indicated amplitude change, was probably somewhat greater than the value which the subject first felt because of the lag in the response of the subject and operator and the finite rate of change of pressure.

In the tests to determine the sensitivity of the subject to frequency change, the procedure was very similar. The shaker was first set into operation at a predetermined amplitude and frequency. The frequency was then changed by manually adjusting a rheostat which controlled the voltage of the frequency-control motor while the air pressure was kept constant. Because of the response characteristics of the stick and shaker combination (fig. 2), the amplitude did not remain constant but changed somewhat with change in frequency at a given pressure. As can be seen in figure 2, the change in amplitude with change in frequency is greater at the higher pressures and the lower frequencies for this particular shaker and stick combination.

For amplitude sensitivity, two tests were made at a frequency of 26 cycles per second and basic amplitudes of 0.014 inch and 0.032 inch and one test at a frequency of 10 cycles per second and a basic amplitude of 0.032 inch. For frequency sensitivity two tests were made with a basic frequency of 18.8 cycles per second and amplitudes of 0.013

and 0.066 inch (4 lb/sq in. and 70 lb/sq in.). There were 2 to 4 subjects for each test with 44 to 91 trials for each subject.

Results.- The results of the amplitude-sensitivity tests are presented in figure 8 as frequency distributions of the ratio of the change in amplitude detected to the basic amplitude $(\Delta A/A)$. The results of the frequency-sensitivity tests are presented in figure 9 as frequency distributions of the ratio of the change in shaker frequency detected to the basic shaker frequency $(\Delta f/f)$. The following is a tabulation of the results of figures 8 and 9:

For amplitude sensitivity,

Basic amplitude, in.	Frequency, cps	$\left(\frac{\Delta A}{A}\right)_{mean}$
0.032	10	0.36
.014	26	.24
.032	26	.16

and for frequency sensitivity,

Basic frequency, cps	Amplitude, in.	$\left(\frac{\Delta f}{f}\right)_{mean}$
18.8	0.013	0.125
18.8	.066	.125

The results indicate that, over the limited conditions covered in the tests, the amplitude sensitivity at a given frequency increased (lower mean value of $\Delta A/A$) with increase in basic amplitude and also increased for a given basic amplitude with increase in shaker frequency. Obviously, Weber's law, which would imply a constant value for the amplitude-change ratio at a constant frequency, does not apply to amplitude sensitivity over the conditions covered in these tests. This increase in amplitude sensitivity with increase in amplitude and frequency indicates that the amplitudes and frequencies used in the tests are in the lower stimulus range. Increase in sensitivity with increase in magnitude of the stimulus is, of course, characteristic of all senses in the lower stimulus range (see refs. 3 to 6). Weber's law generally applies only in the middle of the sensible stimulus range. In regard to higher amplitudes, pilots used as subjects considered about 1/4 inch as a maximum tolerable double amplitude.

The results in figure 9 indicate about the same frequency sensitivity at two different amplitudes. Comparison of the results in figure 9 with those in figure 8 indicates that, for the conditions covered, the subjects were more sensitive to frequency changes than to amplitude changes.

Although the frequency and amplitude tests were conducted over a range of conditions under which stick shakers have been used, this range may not be the optimum for frequency and amplitude sensitivity. Consequently, no direct comparison of these results with those for other senses is made. The sensitivity of other senses to various stimuli may be found in references 1 to 6.

The results in figures 8 and 9 indicate that, in order to insure sensing a change in stick vibration characteristics, up to 100-percent change in amplitude or up to 40-percent change in frequency may be required (changes detected in 100 percent of trials). These values correspond approximately to the changes in stick-vibration frequencies and amplitudes that the subjects were generally able to detect and correct for, as shown in figure 7.

CONCLUDING REMARKS

An exploratory investigation with laboratory apparatus was made to determine whether a pilot could use stick vibration varying in either frequency or amplitude, or both, with angle of attack or lift as an indicator for maintaining a desired margin of angle of attack or lift below the stall. The results of the tests indicate that, once established, a given flight condition can probably be maintained by sensing variations in stick vibration at least over the period of time covered by the tests (35 seconds), provided that allowable variations from the desired flight condition produce either changes in amplitude of vibration of about 100 percent or changes in frequency of about 40 percent, or both. In the ranges of amplitude and frequency covered in the tests, sensitivity to amplitude changes increased with increase in amplitude and frequency; sensitivity to frequency changes did not appear to be materially affected by amplitude. No investigation was made of the effects of extraneous vibrations from other sources on the ability to sense the vibrations produced by the stick shaker.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 27, 1954.

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   Pt. III, ch. II, sec. II, and table 2-1.
   Pt. IV, ch. II, sec. I, and tables 1-1, 1-2, and 1-3.
   Pt. V, ch. II, sec. I, and table 1-4,
   Pt. V, ch. II, sec. II, and table 2-3C.

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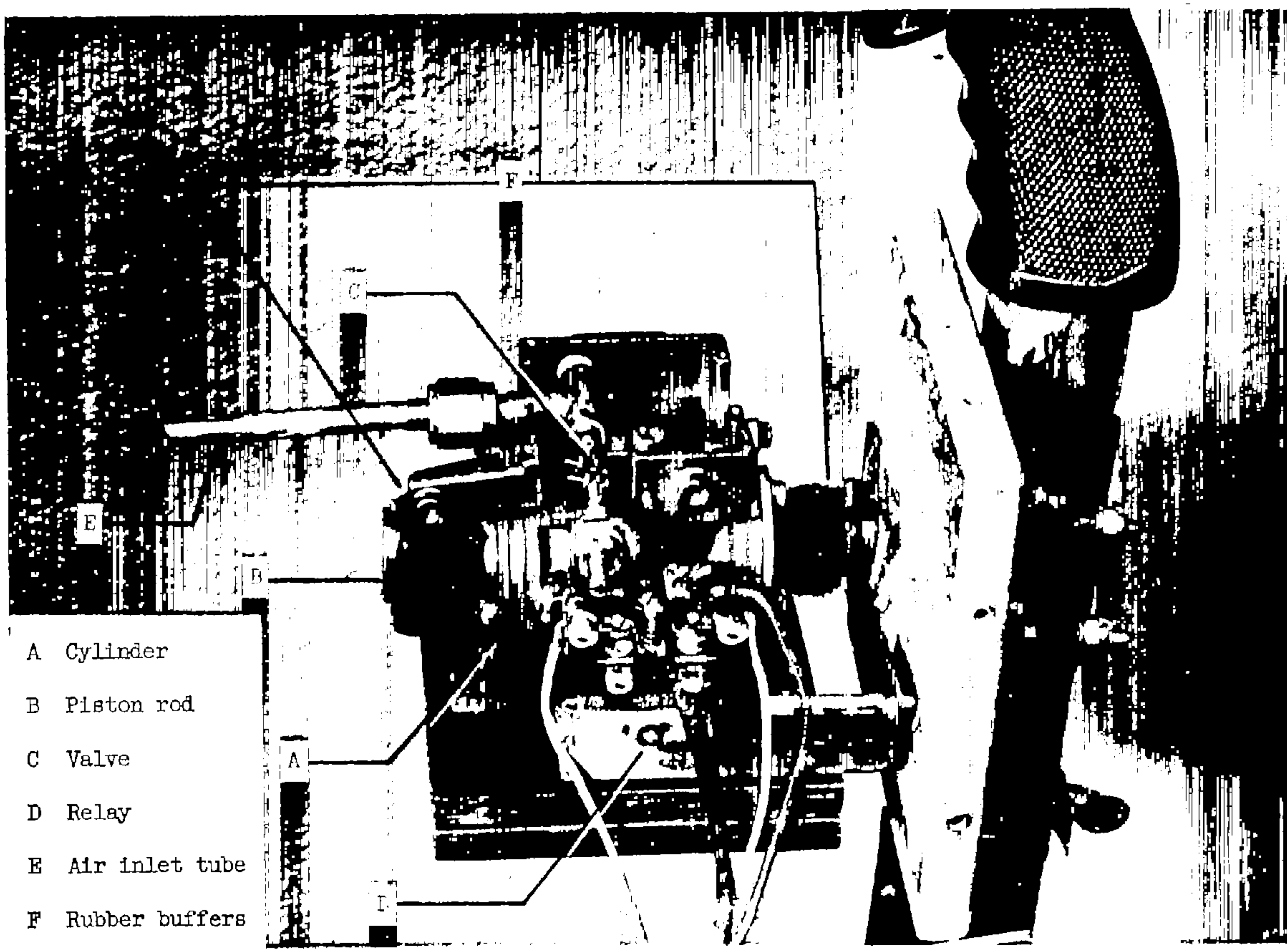

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Figure 1.- Photograph of stick shaker.

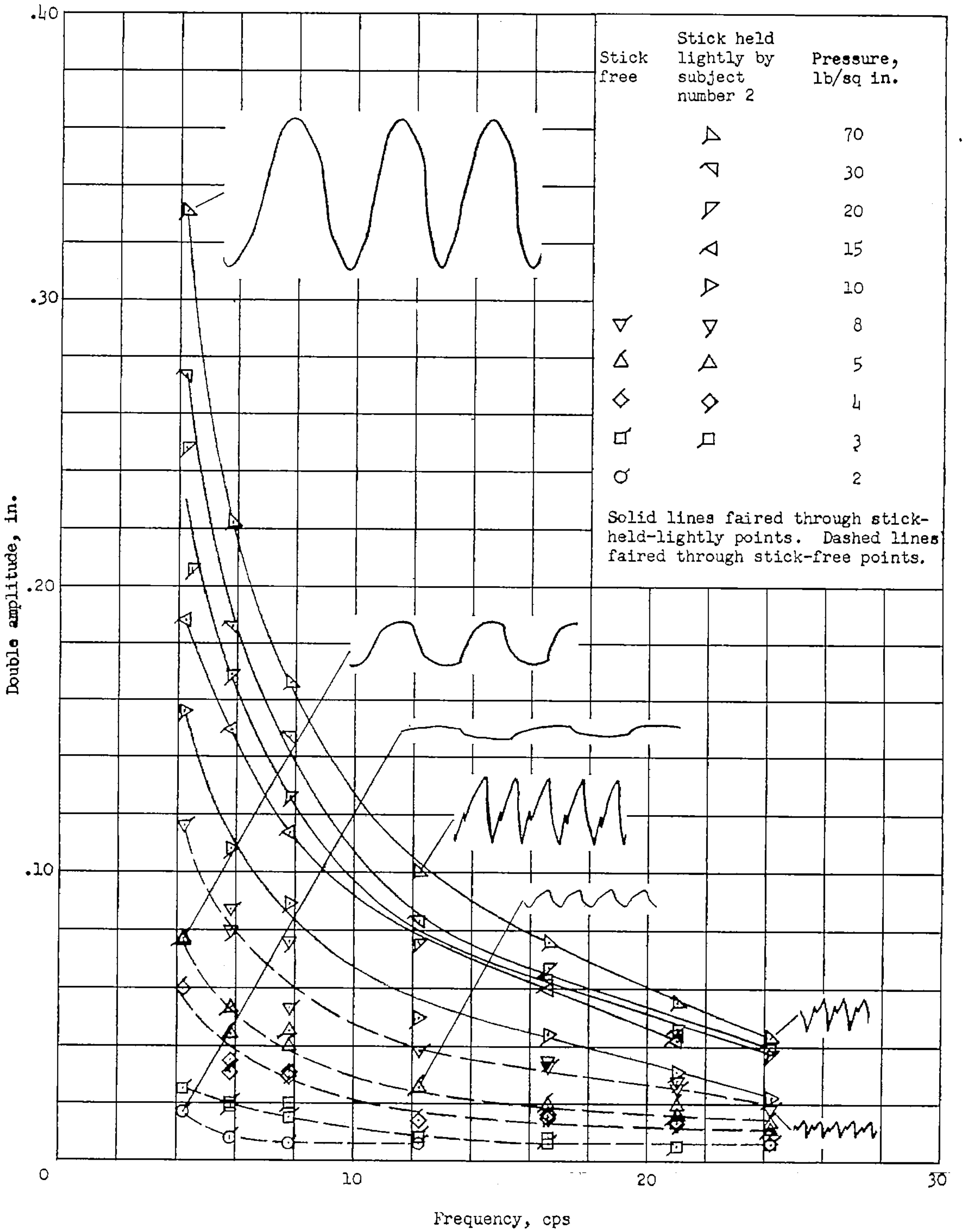


Figure 2.- Frequency-response calibration of stick and shaker combination for shaker with rubber buffers. Lines fairing the data points are for constant pressure. Typical wave forms are shown at indicated points.

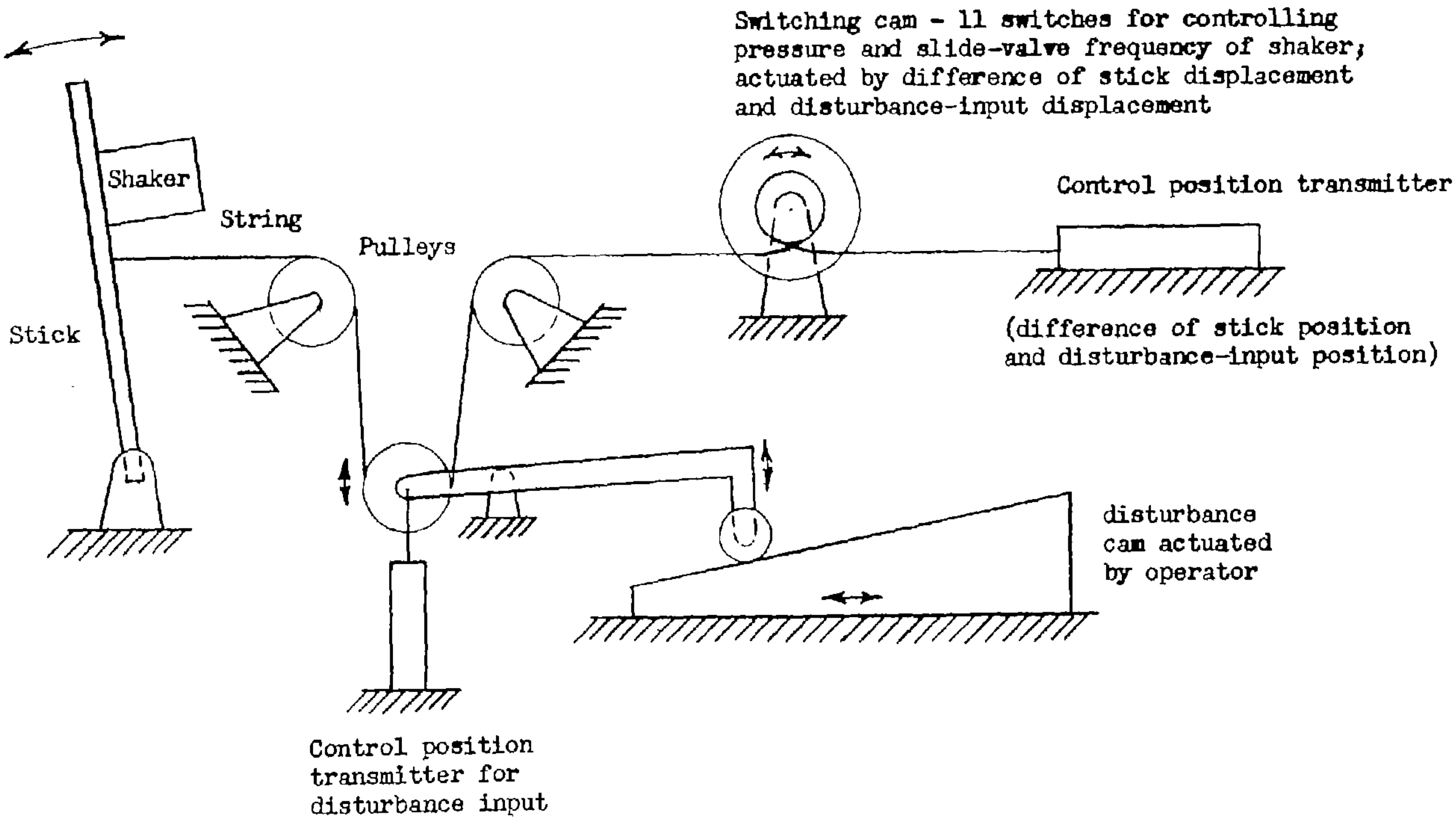
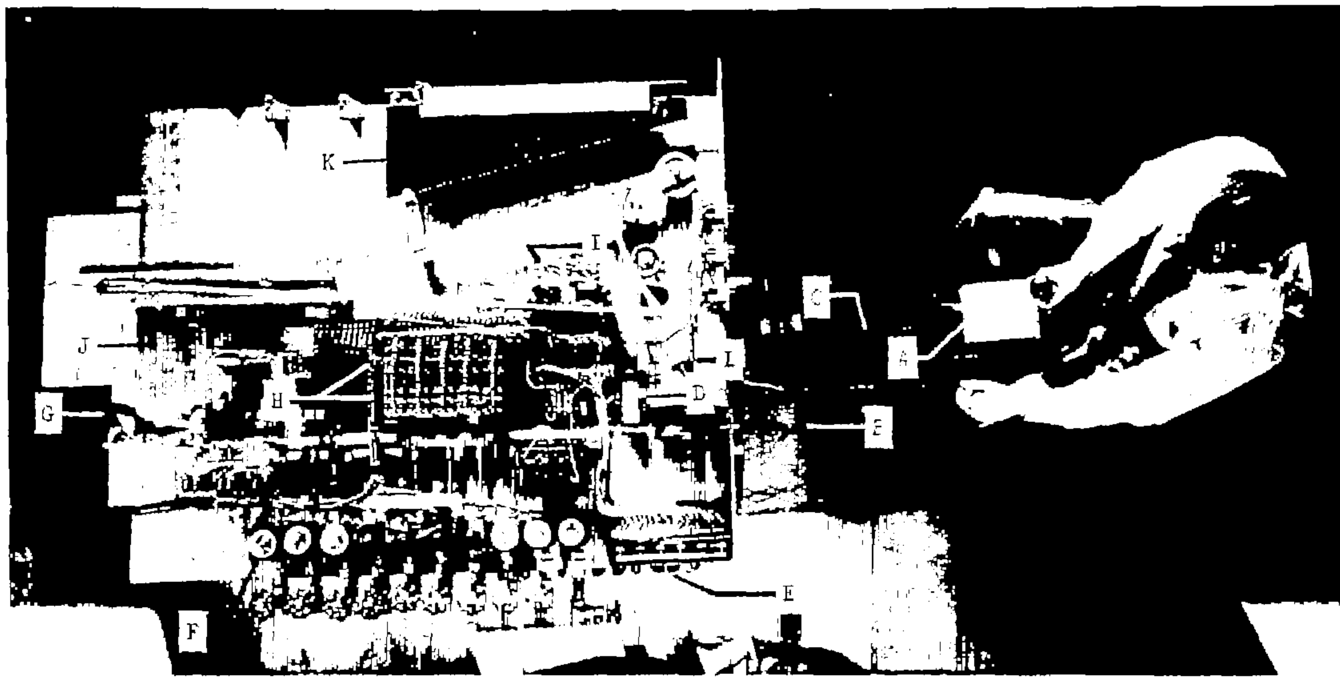


Figure 3.- Schematic diagram of the arrangement for imposing an arbitrary input of frequency and amplitude of stick vibration, for allowing the subject to compensate for the arbitrary input, and for measuring the subject's performance.



A Box containing shaker

B Input air hose to shaker

C String from stick

D Motor controlling frequency

E Rheostats

F Valves controlling pressure to shaker

G Air supply hose

H Relays

I Output or switching cam

J Output control position transmitter

K Disturbance-input cam

L Disturbance-input control position transmitter

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Figure 4.- Photograph of stick-shaker equipment with subject ready for test.

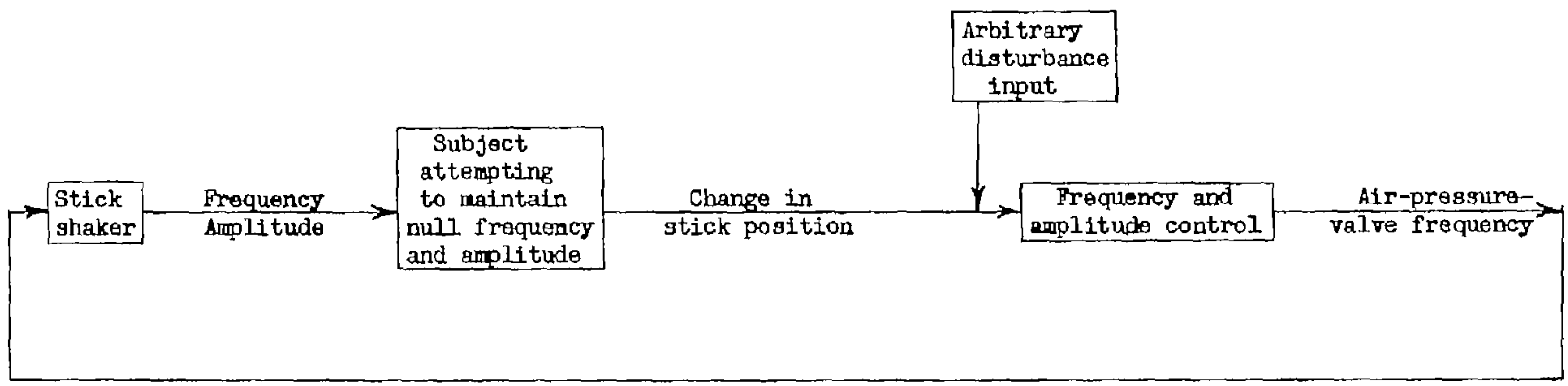
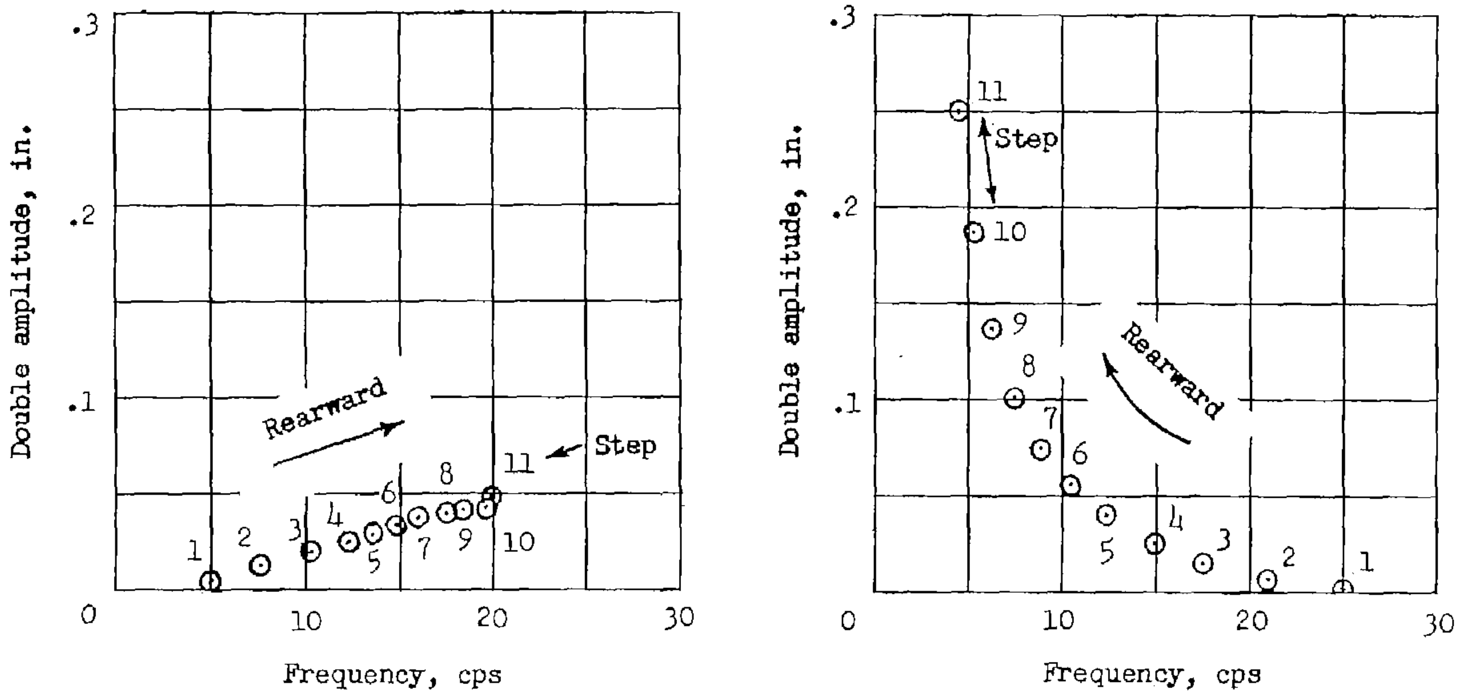


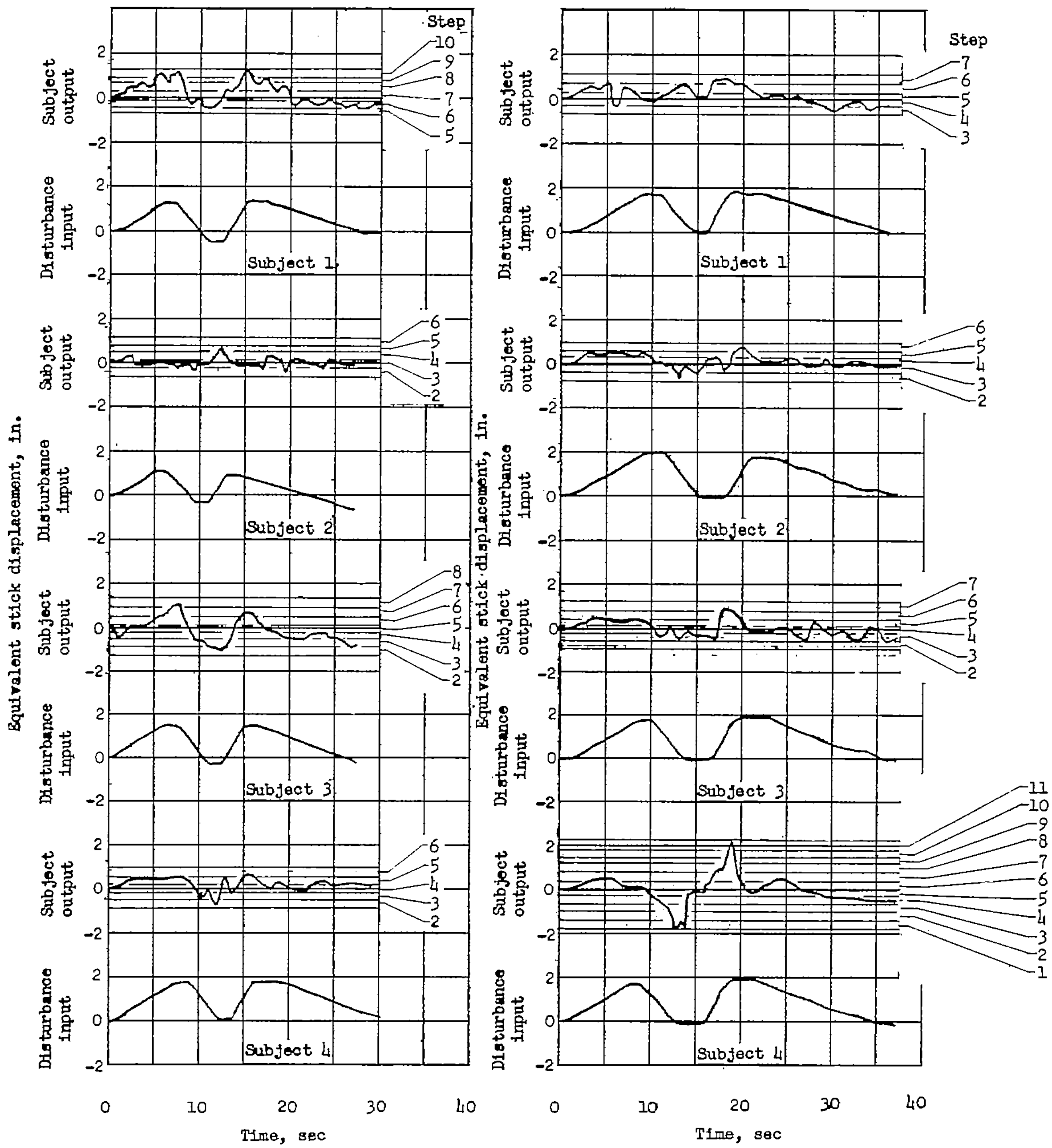
Figure 5.- Block diagram illustrating the ideal functional characteristics of the apparatus in tests to determine ability of a subject to maintain a selected stick-shaker frequency and amplitude.



(a) Increasing frequency and increasing amplitude with rearward stick displacement (variation A).

(b) Decreasing frequency and increasing amplitude with rearward stick displacement (variation B).

Figure 6.- Variations of frequency and double amplitude of stick-shaker vibration with switching or output cam displacement (in step numbers) used in tests to determine ability of subject to maintain a selected stick-shaker frequency and amplitude.



(a) Increasing frequency and increasing amplitude with rearward stick displacement (variation A).

(b) Decreasing frequency and increasing amplitude with rearward stick displacement (variation B).

Figure 7.- Time histories of disturbance input and subject output in terms of equivalent stick displacement showing ability of subject to maintain a selected stick-shaker frequency and amplitude.

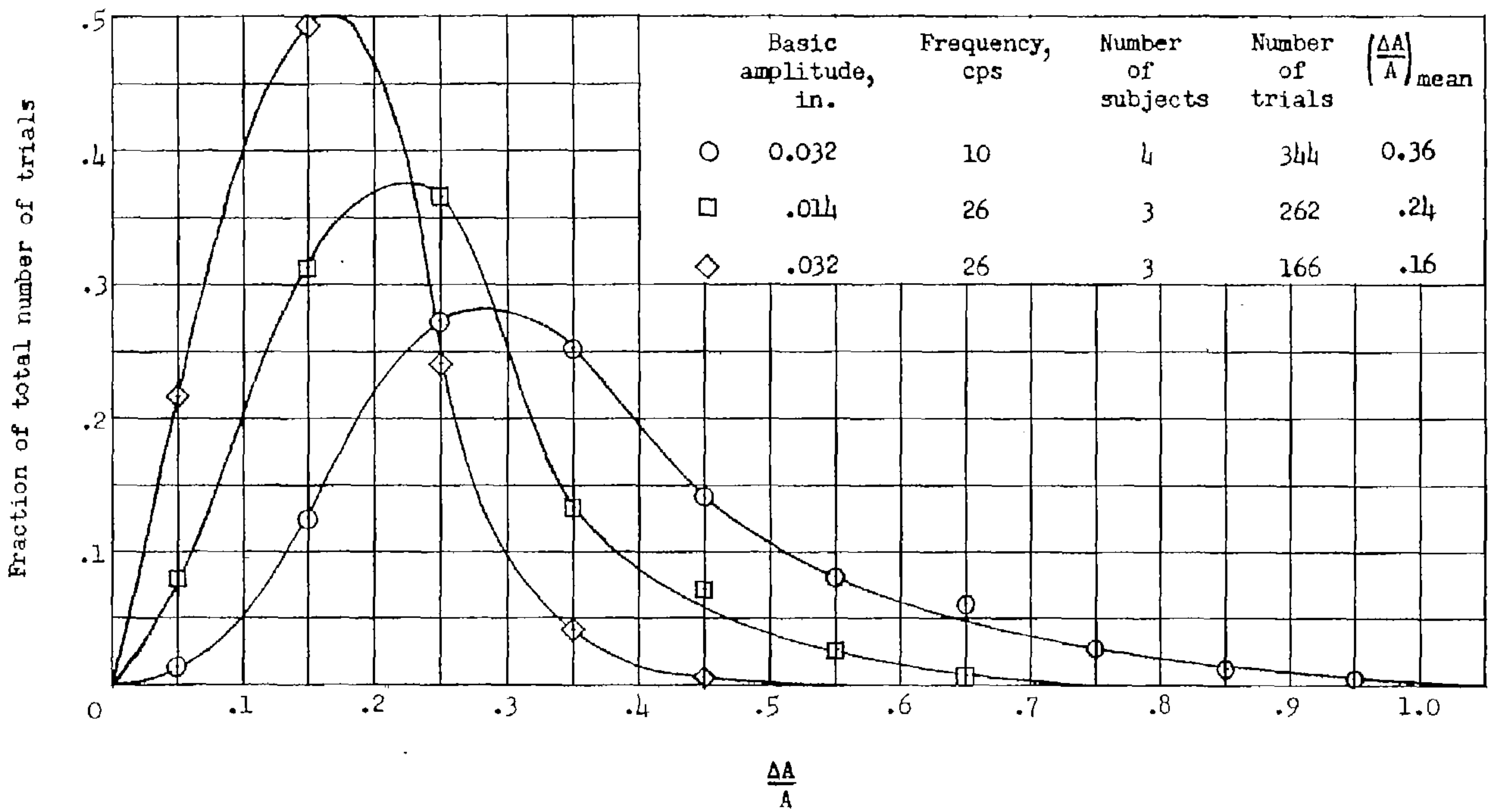


Figure 8.- Frequency distribution of the ratio of change in amplitude of stick vibration detected to the basic amplitude.

	Basic frequency, cps	Constant pressure, lb/sq in.	Approximate constant amplitude, in.	Number of subjects	Number of trials	$\left(\frac{\Delta f}{f}\right)_{mean}$
○	18.8	4	0.013	4	320	0.125
□	18.8	70	.066	2	169	.125

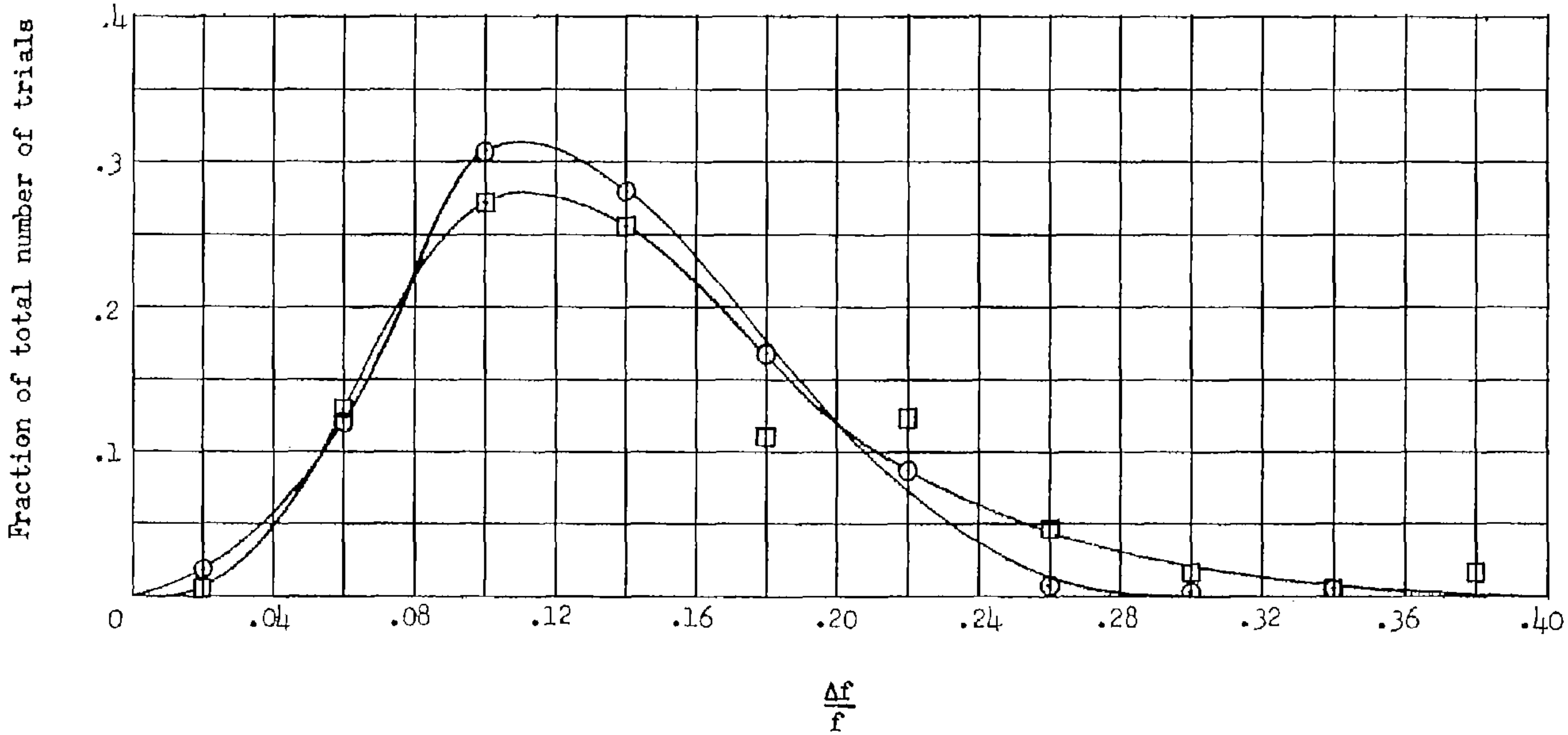


Figure 9.- Frequency distribution of the ratio of change in frequency of stick vibration detected to the basic frequency.

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